Significant primordial star formation at redshifts $z \approx 3-4$.

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Four recent observational results have challenged our understanding of high–redshift galaxies, as they require the presence of far more ultraviolet photons than should be emitted by normal stellar populations. First, there is significant ultraviolet emission from Lyman Break Galaxies (LBGs) at wavelenghts shorter than 912Å[1]. Second, there is strong Lyman α emission from extended "blobs" with little or no associated apparent ionizing continuum[2]. Third, there is a population of galaxies with unusually strong Lyman α emission lines[3]. And fourth, there is a strong HeII (1640 Å) emission line in a composite of LBGs[4]. The proposed explanations for the first three observations are internally inconsistent, and the fourth puzzle has remained hitherto unexplained. Here we show that all four problems are resolved simultaneously if $10-30$ percent of the stars in many galaxies at $z \approx 3-4$ are mainly primordial – unenriched by elements heavier than helium ('metals'). Most models of hierarchical galaxy formation assume efficient intra–galactic metal mixing, and therefore do not predict metal-free star formation at redshifts significantly below $z \sim 5$ [5, 6, 7, 8, 9]. Our results imply that micro–mixing of metals within galaxies is inefficient on a $\sim$ Gyr time–scale, a conclusion that can be verified with higher resolution simulations, and future observations of the HeII emission line.

The continuum emission from LBGs can be explained by adding the continuous formation of massive stars to the standard initial mass function (IMF). In the absence of such a bias in the IMF, the continuum flux emerging just below < 912 Å will be dominated by low–mass stars and will be significantly fainter than observed. The other three puzzles require a substantial increase in the total number of energetic ionizing photons, and we find they cannot be resolved by a bias of the IMF alone. To increase the number of ultraviolet photons further the temperature in the atmospheres of the stars must be increased. This is the case for metal-free (often called population-III) stars, which have significantly reduced opacity owing to the lack of CNO elements [10, 11].

Lyman-continuum flux has been detected [1] in the composite spectrum of 29 Lyman Break Galaxies (LBGs) at a mean redshift of $z \approx 3.4$. Although the authors of ref. 1 warn that sky background subtraction at the low observed flux level is a concern, when taken at face value, their result implies that a surprisingly large fraction of ionizing photons can typically escape from these galaxies. These authors found $f_{\rm esc} \gtrsim 0.5$, where $f_{\rm esc}$ is defined as the ratio of 900Å photons that escape the galaxy and the 1500Å photons that escape (the wavelengths are quoted in the rest–frame of the LBGs). Using more detailed fits of the observed spectrum, [12] and [13] found that the spectrum appears surprisingly blue, even if *no* additional Lyman continuum absorption is assumed to take place in the galaxy (beyond the dust absorption that also affects the spectrum at 1500Å).

We compare the stacked composite spectrum of LBGs in [1] with model galactic spectra, including metal–free stars. The intrinsic emission of the galaxies is modeled as the sum of "normal" star–formation (stellar populations with metallicity ratio $> 10^{-3} Z/\mathrm{Z}_\odot$ [14, 15]), and metal–free, massive pop–III star–formation. For the "normal" component of the intrinsic stellar emission, we use the spectral synthesis models of [16] for a Salpeter IMF (with a slope $\alpha = 2.35$) between $1 - 100\mathrm{M}_\odot$ and a metallicity of $Z = 0.4\mathrm{Z}_\odot$, and compute the spectrum for continuous star formation for 10^8 yr, which is the age for which a steady-state has been reached. For the 'metal–free' component, we use the models of [17], and adopt the same Salpeter IMF, but limited to massive stars in the $100 - 500\mathrm{M}_\odot$ range [18, 19], and with $Z = 0$. Note

that massive stars with $> 100\mathrm{M}_\odot$ have similar spectra, and our results should not depend significantly on the distribution of pop–III stellar masses above this threshold value. To simulate the observed, processed composite spectrum, we modify the emitted stellar template spectrum by including the effects of dust absorption, as well as the opacity of the intervening intergalactic medium (see Supplementary information).

As the top panel in Fig. 1 shows, in the $880\text{Å} \leq \lambda \leq 910\text{Å}$ range, the mean observed flux is quite high, $F_\nu/F_{1500} = 0.064 \pm 0.013$; while the normal–only star formation model predicts a much lower value of $F_\nu/F_{1500} = 0.023 \pm 0.01$. Taken at face value, the data reveals an ionizing flux about three times higher than this model predicts, even if we do not include any continuum absorption by neutral gas in the galaxy. The data and the model do not agree at the $> 3\sigma$ level. The model with pop–III star–formation with $f_{\rm popIII} = 0.5$ almost generates the observed ionizing flux in the $880\text{Å} \leq \lambda \leq 910\text{Å}$ range; producing a mean $F_\nu/F_{1500} = 0.048 \pm 0.02$.

Our conclusions regarding the LBGs apply to the bluest sub-sample. This is further supported by the analysis of the CIV absorption line associated with the stellar winds in massive stars that is observed in the spectra of LBGs. According to our prediction, the bluest LBGs should have weaker CIV absorption than the reddest LBGs, because pop-III stars are metal free and therefore contribute significantly fewer metals. This trend is indeed what is observed (see table 3 and section 5.3 in [4]). Detailed inspection of the numbers in table 3 of [4] shows that the weaker strength of the CIV line requires an abundance of $\sim 50\%$ pop-III in the bluest LBGs. We note that the CIV profile in LBGs is a complex superposition of interstellar absorption, stellar-wind emission and absorption, and possibly nebular emission. Our models predict that the trend of decreasing CIV strengh in the bluest galaxies is present in the narrow interstellar absorption and any broad stellar component (which measures the total cumulative C output of all stars), but not necessarily in any of the other components. The fact that metal lines are observed in all LBGs indicates that LBGs are not composed purely of pop-III stars, but that there is a mixture in each galaxy of pop-III and normal stars.

There have been recent observations of a population of 35 Lyα blobs at $z = 3.1$ in narrow and broad band spectra[2]. For about one third of the blobs, the amount of photons provided by a normal stellar population that fits the observed spectrum at wavelengths longer than 912 Åis not capable of producing the required number of ionizing photons to explain the observed Lyα flux. If we assume case B (two Lyα photons are produced for every three ionising photons from the stars) then a stellar population with $Z = 10^{-2}\mathrm{Z}_\odot$ would produce at least 35% less photons than those necessary to account for the observed Lyα flux. To reproduce the observed flux, about 30% of the stars would need to be metal-free.

Figure 2 shows that about $20 - 30\%$ of the blobs also have continuum colors consistent with the stars producing the ionizing Lyα photons being metal-free. The fact that the stellar populations powering the extended emission are metal–poor is consistent with the fact that these sources are extended, and are presumably more likely to have been caught in the process of their assembly, when they are less metal–enriched overall . They could plausibly be identified, therefore, as the progenitors of LBGs. The rest-frame equivalent width for Lyα ranges from 20 to 350 Å. For models with constant star formation and $Z > 10^{-5}\mathrm{Z}_\odot$ the EW are $70 - 100$ Å. About one third of the blobs have EW larger than 100 Å and therefore require metal-free stars. This is in agreement with what is found for the colors, although we note that there is little overlap among the individiual blue blobs and those with Lya excess. The good fit to the $B - I$ colors, without including (case-B) reprocessing of ionizing radiation into Lyman α, implies that $f_{\rm esc}$ is of the order of 100% because a smaller escape fraction would imply more flux on B and therefore significantly bluer $B - I$ colors than those observed. The large escape fraction of ionizing radiation would be consistent with the value observed in the composite of LBG spectra.

Strong HeII (1640 Å) emission line from a composite of LBGs has been observed [4]. They report equivalent widths for a sample of several hundred LBGs of about 2 Å. This line is also very broad, with a FWHM of about 1500 km s^{-1}. Although this cannot be explained by stars without winds, it has been shown (e.g. [20, 21]) that, aided by rotation, metal–free stars can loose significant amounts of mass and drive strong winds, similar to normal–metalicity stars. In this case, the He–ionizing photons from

the massive popIII stars will be reprocessed in the optically thick stellar outflows surrounding the star, making the line broad [22]. As discussed in [4], normal WR stars cannot explain the HeII line observed in the composite LBG sample, because the requisite number of WR stars will overproduce the stellar CIV emission.

However, metal-free massive stars with winds do not have this problem. As shown in [22] there is a clear anti-correlation between the strength of the HeII 1640 line and the CIV line (see Fig. 13 in [22] for the case $Z = 0.01$ and $10^{-4} Z_{\odot}$). For metal-free stars the equivalent width of the HeII 1640 line for a continuous star forming (1 $M_{\odot}$ yr^{-1}) model of metal-free stars at age 0.1 Gyr is 30 Å, significantly larger than observed. So for this sample, the required amount of metal-free stars is only 10%. However, the equivalent width of the HeII 1640 line is very sensitive to the metallicity. If we use $Z = 10^{-7} Z_{\odot}$ (instead of $Z = 0$), then the 912 Å decrement doesn't change, so our conclusions above about the UV radiation from LBGs and the Lyα blobs remain unchanged. But the He-ionizing flux, and the He1640 equivalent width is reduced by about a factor of $6 - 7$. This implies a population of $\sim 30\%$ metal-free stars.

Recent non–detections of the HeII 1640 line in a composite spectrum of 17 galaxies at $z = 4.5$ [23], as well as from an individual Lyα emitter at $z = 6.33$ [24] have provided tight upper limits, but still allow for a significant mass fraction ($\sim 50\%$) in Pop III stars.

The Large Area Lyman Alpha survey [3] reports large Lyα equivalent widths for a sample of 150 emitters at $z \approx 4.5$. The median value of the distribution is ~ 450 Å and 60% have equivalent widths above 240 Å. No continuum emission was found in 30% of the emitters. However, the equivalent widths are spread over a wide range: from 10 to 5000 Å. This implies that not a single type of stellar population can account the large spread of equivalent widths. The first suggestion that this large equivalent widths can be produced by very low metallicity stars is found in [30]. We find that for metal-free stars and constant star formation, the equivalent width is 1000Å for the IMF used in this paper and declines to 300Å for a Salpeter IMF [17]. We performed a more detailed fit to the distribution in [3]. Using models

for metallicities $Z > 10^{-5} Z_{\odot}$ we find that bursts of ages greater than 10^7 years have equivalent widths as large as 300Å whereas constant star formation models have about 200Å. Therefore "normal" stellar populations can account for as much as 40% of the Lyα emitters, while the rest need to be accounted for by metal-free stellar populations.

Recently two stars with metallicity $Z < 10^{-5} Z_{\odot}$ have been found in the Milky Way [25]. Although such low–mass stars ($\lesssim 0.8$ $M_{\odot}$) are not included in our model, they reveal the details of the earliest stages of chemical enrichment, and suggest an initial overproduction of Carbon. For stars with $[Fe/H] < -3.5$, 40% have $[C/Fe] > 1.0$ [26] and the trend increases to 100% for stars with $[Fe/H] < -5$. This trend can naturally arise in our model [20, 21].

Our results imply that micro–mixing of metals within galaxies is inefficient on a $\sim$ Gyr time–scale, a conclusion that may be surprising, as current models of hierarchical galaxy formation assume efficient intra–galactic metal mixing, and therefore do not predict metal-free star formation significantly below $z \sim 5$ [5, 6, 7, 8, 9]. However, the presence of significant pockets of metal–free star–formation explains four puzzling observational results, and the hypothesis does not violate any other existing observations. The presence of metal–free gas pockets can be verified in future high resolution numerical simulations, and by future observations. Our models predict that in some of the LBGs there should be a detectable continuum shortward of 912Å and a detectable individual HeII line. Long–integration observations of these individual galaxies in the future could be used tocharacterize their spectra, and to confirm the presence of metal-free stellar populations. In particular we predict that there should be a clear anti-correlation between He1640 and CIV line strength and this should be a reliable test of the amount of metal-free stars at $z \sim 3 - 5$.

References

[1] Steidel, C. C., Pettini, M., & Adelberger, K. L., Lyman-Continuum Emission from Galaxies at $Z \sim 3.4$, Astrophys. J., 546, 665-671(2001).

[2] Matsuda, Y. et al., A Subaru Search for Lyalpha Blobs in and around the Protocluster Region At Redshift $z = 3.1$, Astrophys. J., 128, 569-584 (2004).

[3] Malhotra, S., & Rhoads, J. E., Large Equivalent Width Lyalpha line Emission at $z = 4.5$: Young Galaxies in a Young Universe?, Astrophys. J., 565, L71-L74 (2002).

[4] Shapley, A. E., Steidel, C. C., Pettini, M., & Adelberger, K. L., Rest-Frame Ultraviolet Spectra of $z \sim 3$ Lyman Break Galaxies, Astrophys. J., 588, 65-89 (2003).

[5] Madau P., Ferrara A., Rees M. J., Early Metal Enrichment of the Intergalactic Medium by Pregalactic Outflows, Astrophys. J., 555, 92-105 (2001).

[6] Scannapieco E., Schneider R., Ferrara A., The Detectability of the First Stars and Their Cluster Enrichment Signatures, Astrophys. J., 589, 35-52 (2003).

[7] Norman M. L., O'Shea B. W., Paschos P., Did Massive Primordial Stars Preenrich the Lyalpha Forest?, Astrophys. J., 601, L115-L118 (2004).

[8] Yoshida N., Bromm V., Hernquist L., The Era of Massive Population III Stars: Cosmological Implications and Self-Termination, Astrophys. J., 605, 579-590 (2004).

[9] Bromm V., Loeb A., High-Redshift Gamma-Ray Bursts from Population III Progenitors, astro, arXiv:astro-ph/0509303 (2005)

[10] Tumlinson J., Shull J. M., Zero-Metallicity Stars and the Effects of the First Stars on Reionization, Astrophys. J., 528, L65-L69 (2000).

[11] Bromm V., Kudritzki R. P., Loeb A., Generic Spectrum and Ionization Efficiency of a Heavy Initial Mass Function for the First Stars, Astrophys. J., 552, 464-472 (2001).

[12] Hui, L., Haiman, Z., Zaldarriaga, M., & Alexander, T., Connections between the Cosmic Baryon Fraction, the Extragalactic Ionizing Background, and Lyman Break Galaxies, Astrophys. J., 564, 525-533 (2002).

[13] Haehnelt, M., Madau, P., Kudritzki, R., & Haardt, F., An Ionizing Ultraviolet Background Dominated by Massive Stars, Astrophys. J., 549, L151-L154 (2001).

[14] Bromm V., Ferrara A., Coppi P. S., Larson R. B., The fragmentation of pre-enriched primordial objects, Mon. Not. R. Astron. Soc., 328, 969-976 (2001).

[15] Schneider R., Ferrara A., Natarajan P., Omukai K., First Stars, Very Massive Black Holes, and Metals, Astrophys. J., 571, 30-39 (2002).

[16] Leitherer, C., Schaerer, D., Goldader, J. D., Delgado, R. M. G., Robert, C., Kune, D. F., de Mello, D. F., Devost, D., & Heckman, T. M., ApJS, 123, 3-30 (1999); electronic data are available at http://www.stsci.edu/science/starburst99/

[17] Schaerer, D., The transition from Population III to normal galaxies: Lyalpha and He II emission and the ionising properties of high redshift starburst galaxies, Astron. Astrophys., 397, 527-538 (2003).

[18] Abel T., Bryan G. L., Norman M. L., The Formation of the First Star in the Universe, Science, 295, 93-95 (2002).

[19] Bromm V., Coppi P. S., Larson R. B., The Formation of the First Stars. I. The Primordial Star-forming Cloud, Astrophys. J., 564, 23-51 (2002).

[20] Marigo P. et al., Zero-metallicity stars. II. Evolution of very massive objects with mass loss, Astron. Astrophys., 399, 617-630 (2003).

[21] Meynet, G., Ekstrom, S., Maeder, A. The early star generations: the dominant effect of rotation on the CNO yields. ArXiv Astrophysics e-prints arXiv:astro-ph/0510560 (2005).

[22] Kudritzki, R. P. Line-driven Winds, Ionizing Fluxes, and Ultraviolet Spectra of Hot Stars at Extremely Low Metallicity. I. Very Massive O Stars. Astrophysical Journal 577, 389-408 (2002).

[23] Dawson, S., et al., Spectroscopic Properties of the z   4.5 Lyalpha Emitters, Astrophys. J., 617, 707-717 (2004).

[24] Nagao T., Motohara K., Maiolino R., Marconi A., Taniguchi Y., Aoki K., Ajiki M., Shioya Y., An Observational Pursuit for Population III Stars in a Lyalpha Emitter at z = 6.33 through He II Emission, Astrophys. J., 631, L5-L8 (2005).

[25] Christlieb N., et al., A stellar relic from the early Milky Way, Nature, 419, 904-906 (2002).

[26] Beers T. C., Christlieb N., The Discovery and Analysis of Very Metal-Poor Stars in the Galaxy, ARA&A, 43, 531-580 (2005).

[27] Schaerer, D., & de Koter, Combined stellar structure and atmosphere models for massive stars. III. Spectral evolution and revised ionizing fluxes of O3-B0 stars., Astron. Astrophys., 322, 598-610 (1997).

[28] Najarro, F., Kudritzki, R. P., Cassinelli, J. P., Stahl, O., & Hillier, D. J., Stellar winds and the EUV continuum excess of early B-giants, Astron. Astrophys., 306, 892-890 (1996).

[29] Jimenez, R., MacDonald, J., Dunlop, J. S., Padoan, P., & Peacock, J. A., Synthetic stellar populations: single stellar populations, stellar interior models and primordial protogalaxies, Mon. Not. R. Astron. Soc., 349, 240-254 (2004).

[30] Kudritzki, R. P. et al. Discovery of nine Lyalpha emitters at redshift $z \approx 3.1$ using narrowband imaging and VLT spectroscopy. Astrophys. J. 536, 19-30 (2000).

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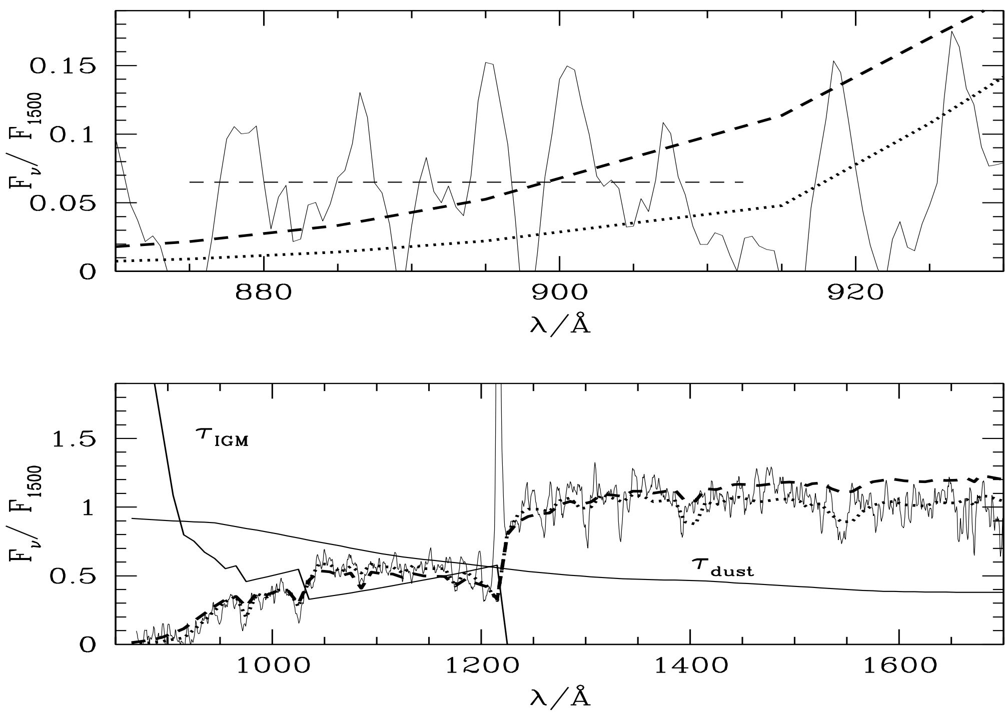
Figure 1: Lyman break galaxies stacked observed spectrum and best fit population synthesis models. The dotted curve corresponds to continuous normal star formation for 10^8 years, and the dashed curve corresponds to a mix model where 50% of the stars (by mass) are massive, metal–free stars in the $100 - 500$ $M_{\odot}$ range. The solid curves show the composite spectrum in [1]. All fluxes are normalized to the flux at the emitted wavelength of 1500Å. For reference, in the bottom panel, we show the optical depths assumed for the dust and the IGM. In the top panel, the horizontal dashed line shows the mean observed flux in the interval 880Å$\leq \lambda \leq$ 910Å. The inference is that the spectrum requires a significant contribution by metal–free star–formation, with a mass–fraction $f_{\rm popIII} \approx 0.5$. As discussed in [12], changing the assumed metallicity of the normal stars does not significantly increase the predicted ionizing fluxes. The ultraviolet fluxes of OB stars can be increased by the presence of stellar winds (not included in the stellar models we adopted). Although winds can increase the HeII–ionizing flux by orders of magnitude, the corresponding increase for the H–ionizing flux in O stars has been found to be small [27]. The increase can be more significant for cooler B–stars [28], but these stars do not dominate the ionizing photon budget in the continuous star–formation models, in which O–stars are continuously replenished. Furthermore, the hydrostatic stellar models typically reproduce the properties of Galactic HII regions [16], so that an increase by the required factor of ~ 2 would make it more difficult to reconcile the models with these observations.

Figure 2: Colour distributions of the Lyα blobs. The different lines correspond to stellar population models with continuous star formation at an age of 10^8 yr for $Z = 0.2Z_{\odot}$ (dashed), $Z = 0.01Z_{\odot}$ (dotted) (both computed using the models from [29]) and $Z = 0$ (solid, assuming an IMF and mass range $100 - 500$ $M_{\odot}$ as in our analysis of LBG spectra). We have included the effect of the opacity of the intervening intergalactic medium. The shaded ranges indicate the range of expected colors as various properties of the metal–free population are varied, such as their age (between $10^5 - 10^8$yrs), the IMF (for the three models given in ref. [17]), and star–formation history (between a burst and continuous star formation at a constant rate). All three colour histograms suggest that about 20% of the blobs need to be made of purely popIII stars. Note that no correction was made in the LAB colours for Lya line emission or for

possible continuum contribution from foreground and background objects.



0.15
0.1
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F_ν / F_{1500}
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900
920
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1.5
1
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0
τ_{IGM}
τ_{dust}
1000
1200
1400
1600

Figure 1:

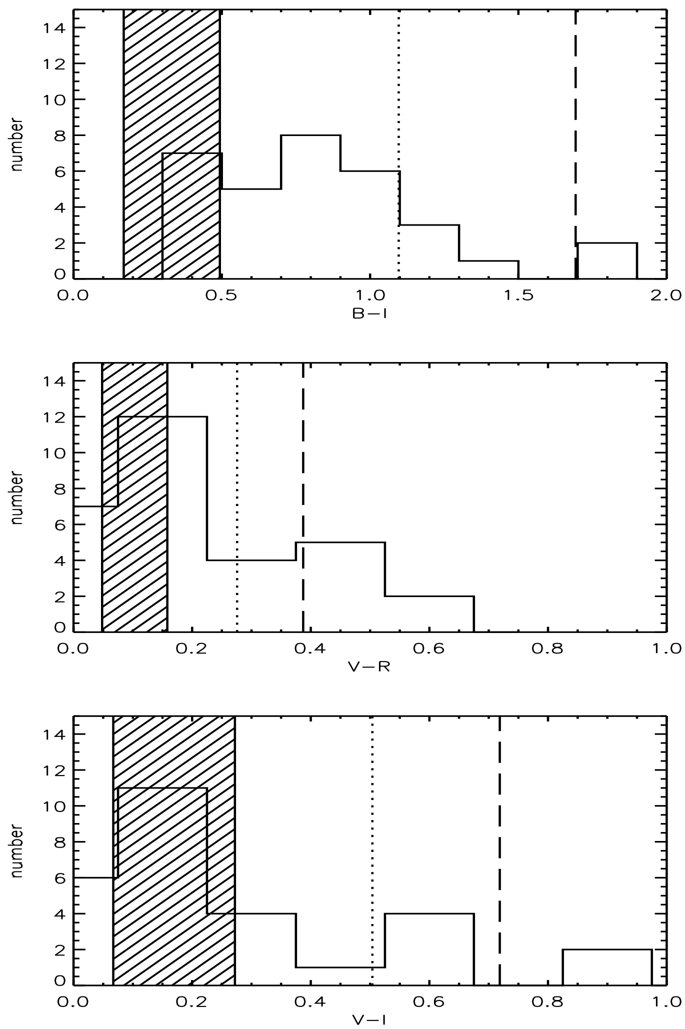

Figure 2: